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Assessment of the technical and economic potentials of biomass use for the production of steam, chemicals and polymers

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ABSTRACT

Fossil fuel substitution with biomass is one of the measures to reduce carbon dioxide (CO_2) emissions. This paper estimates the cost-effectiveness of raising industrial steam and producing materials (i.e. chemicals, polymers) from biomass. We quantify their long-term global potentials in terms of energy saving, CO_2 emission reduction, cost and resource availability. Technically, biomass can replace all fossil fuels used for the production of materials and for generating low and medium temperature steam. Cost-effective opportunities exist for steam production from biomass residues and by substitution of high value petrochemicals which would together require more than 20 exajoules (EJ) of biomass worldwide in addition to baseline by 2030. Potentials could double in 2050 and reach 38–45 EJ (25% of the total industrial energy use), with most demand in Asia, other developing countries and economies in transition. The economic potential of using biomass as chemical feedstock is nearly as high as for steam production, indicating its importance. The exploitation of these potentials depends on energy prices and industry's access to biomass supply. Given the increasing competition for biomass from several economic sectors, more resource efficient materials need to be developed while steam production is already attractive due to its high effectiveness for reducing CO_2 emissions per unit of biomass.

Contents

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1. Introduction

Global manufacturing industry used 127 exajoules (EJ) of final energy in 2008. This is equivalent to one-third of the total final energy use worldwide [1]. 70 EJ of the total industrial energy use was related to process heat in the form of direct heat (including thermal oil) or as steam (including hot water). Energy used in blast furnaces and coke ovens for iron and steel production (11 EJ), as feedstocks for chemicals and polymers production (22 EJ) and electricity use (25 EJ) reached in total 57 EJ [1]. Non-OECD countries[1] account for 60% of the total demand worldwide. Both global industrial energy use and the related greenhouse gas (GHG) emissions are projected to rise as a result of production increase in these countries. Depending on the region, total industrial energy demand is expected to increase by between 50% and 200% by 2050 compared to 2008 [2]. During the 2011 United Nations Climate Change Conference in Durban, countries decided to agree on an emission reduction target no later than 2015 [3]. Some regions are already active in developing long-term emission reduction plans. For example, European Union developed a roadmap to reduce its total GHG emissions by approximately 80% by 2050 as compared to 1990, with a foreseen decrease of carbon dioxide (CO_2) emissions from industry by around 85% [4]. A number of technology options exist to reach these goals, namely improving industrial energy efficiency [5,6], developing and implementing CO_2 capture technologies [7], improving post-consumer waste treatment options [8,9] and switching from fossil fuels and feedstocks to less CO_2 emission-intensive alternatives [2,10–12].

This paper focuses on the potentials of using biomass as fuel to generate process heat (consumed in all sectors of the industry) and as feedstock to produce chemicals and polymers (from now on jointly referred to as materials). Among the six main renewable energy resources (i.e. bioenergy, solar, geothermal, hydro, wind, ocean), bioenergy is projected to contribute the most to the economy-wide energy demand in the long term, also in the industry sector [13–15]. However, limited attention has so far been paid to the assessment of its potentials for the industry sector [11,16]. The objectives of this paper are therefore (i) to conduct a technical and economic assessment of the opportunities of industrial biomass use for the production of steam and materials and (ii) to provide first estimates of the potentials of biomass use in industry in 2030 and 2050.

In the next section, we provide background information about the current situation of industrial biomass use. In Section 3, we explain the methodologies for the economic and environmental assessment of industrial steam and materials production from biomass, and the scenario analysis. In Section 4, we present the results for the current situation and 2030, and subsequently quantify the industrial biomass use potential until 2050. We then critically discuss our findings, paying particular attention to the technology development and policy needs based on the barriers to reaching the estimated potentials (Section 5). We end this paper in Section 6 with conclusions and recommendations for the industry and policy makers.

[1] Organization for Economic Cooperation and Development (OECD) includes industrialized and high-income countries. Non-OECD countries include developing countries and economies in transition.

2. Current situation, available technologies and deployment potentials

Industrial processes are operated in a wide temperature range and the temperature level determines the fuel and technology choice for heat generation. For example, many processes of the food (e.g. drying, washing) and the textile (e.g. dyeing, bleaching) industries operate below 150 °C. Distillation processes and reactors of the chemical industry operate above 250 °C. Temperatures are even higher for the iron and steel production processes (see Fig. 1). While low and medium temperature process heat is typically supplied via steam, high temperature applications require direct heat, for example in cement kilns. Currently, low (< 150 °C), medium (150–400 °C) and high (> 400 °C) temperature processes account for 32%, 23% and 45% of the total industrial process heat demand, respectively (see Fig. 1) [1,17].

Steam is generated at conversion efficiencies which reach above 85% [18]. Today, about 90% of the fuel use for process heat generation is supplied by fossil fuels, and the remainder is from renewable energy sources especially for pulp and paper production [1]. Typical renewable energy sources are wood waste (e.g. bark, black liquor) used in the pulp and paper sector and charcoal use in small-scale blast furnaces in Brazil [1,11].

Large potentials exist for biomass use to generate steam [19,20]. Depending on the technology, fuel type and its features (e.g. moisture content of biomass), the temperature and pressure of steam differ [21]. Biomass could provide low and medium temperature steam [22] as well as electricity [19,23] by technologies such as: (i) fixed bed boilers (from a few kW_{th} up to 20 MW_{th}), (ii) fluidized bed boilers (> 20–30 MW_{th}), (iii) biomass gasifiers (from syngas), and (iv) co-firing [13,19,24]. Among the bioenergy options for energy supply, this paper excludes electricity generation and instead focuses on the production of low and medium temperature steam in boilers and combined heat and power (CHP) plants.

Nearly all feedstock energy currently originates from fossil fuels (22 EJ) but some biomass is also used (0.6 EJ). These feedstocks are converted to plastics, ammonia, methanol, carbon black, carbides and other synthetic organic materials. In total, approximately 350 megatonnes (Mt) of synthetic organic materials were produced in 2008 (see Fig. 2).[2]

About 85% of the total current production of synthetic organic materials are plastics and fibres (~290 Mt/yr). Their production is expected to continue to grow [2]. This creates potentials for switching to biomass for feedstock purposes[3] [25]. Gielen et al. [26] discuss four

[2] Worldwide a total of 27 Mt primary biomass was consumed for the production of bio-based products. This includes:

- a total of 20 Mt primary biomass used for the production of 9.6 Mt/yr (primarily mature) bio-based products, i.e. 4 Mt/yr non-food starch products (excluding quantities used for ethanol and for corrugating and paper making), 4.2 Mt/yr man-made cellulosic fibres and other cellulosic products, 1 Mt/yr alkyd resins and 0.4 Mt/yr (including polylactic acid (PLA)) emerging bio-based monomers and polymers [25]. This requires a total of 0.3 EJ of biomass use as feedstock, assuming a lower heating value (LHV) of 17.5 GJ per tonne of biomass.
- a total of 7 Mt oleochemicals which are derived from fatty acids, fatty alcohols and glycerol (by-product of biodiesel production) (see Fig. 2) (11.5 Mt vegetable oils; [28]). This is equivalent to 0.3 EJ of biomass use as feedstock, assuming a LHV of 37 GJ per tonne of oleochemical.

[3] Synthetic rubber could be produced from isobutylene based on renewable resources [29] and today's share of surfactants and solvents produced from renewable feedstocks could be further increased based on a wide range of feedstocks including oleochemicals, sugars and proteins (e.g. [30,31]).

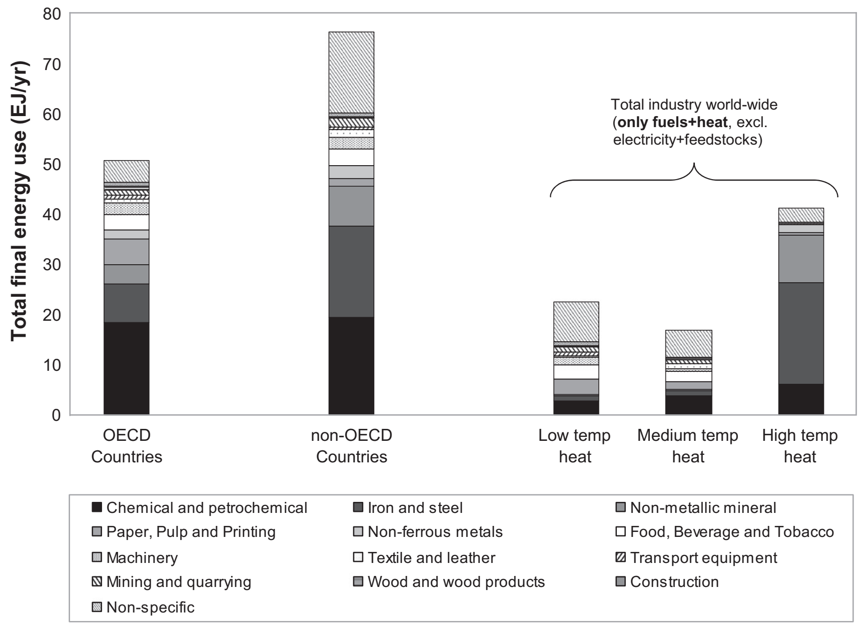

Fig. 1. Sectoral breakdown of total final industrial energy use in OECD and non-OECD countries (including feedstock, electricity use) and breakdown of global final industrial process fuel use by temperature level of steam, 2008.
Sources: [1,17].

principal ways to produce materials from biomass: (i) direct use of naturally occurring polymers, (ii) thermo-chemical conversion of biomass (iii) industrial (or "white") biotechnology, and (iv) "Green" biotechnology using genetically modified crops tailored to the needs of material production. The first three technologies are already partly applied and could be further deployed. The fourth option is still under development. Substitution of materials is determined by their characteristics and the functions of the products to be replaced [27]. We identify three categories of bio-based materials: (i) same compounds (e.g. bio-based polyethylene (PE) from bio-ethanol), (ii) materials with comparable functionality (e.g. PLA to substitute polyethylene terephthalate (PET), polytrimethylene terephthalate (PTT) for nylon), and (iii) end-products with different functions (e.g. biodegradable plastics). In this study, we consider the products of the organic chemical industry (i.e. polymers, chemicals) while we exclude the assessment of biomass use as raw material for established materials such as paper or wood products.

3. Methodology

This section describes the methodology we applied to develop the economic and environmental assessment of industrial use of biomass (Section 3.1) and scenario analysis (Section 3.2).

3.1. Economic and environmental assessment

We first analyse the cost-effectiveness of biomass as fuel for steam production and as feedstock for materials production based on *economic* indicators. For steam, we first estimate its production costs from fossil fuels and biomass (boilers and CHP plants[4]), and subsequently its net present value (NPV) from biomass relative to the fossil fuel-fired boilers based on a bottom-up cost analysis (see Appendices A and B). We analyse the cost-effectiveness for two biomass prices, namely low-cost and expensive sources which represent biomass residues and dedicated energy crops, respectively. For materials, we determine the ratio of the current and future production costs or sales prices of comparable materials which originate from manufacturers, literature and the updated BREW model[5] (see Appendix C) [32]. We determine the cost-competitiveness of bio-based materials based on the comparison of these ratios since data is inadequate for bottom-up cost analysis.[6] All economic data is provided in 2009 real US Dollars (USD). We choose the cost-effectiveness as the only criteria to estimate the potentials of biomass as earlier studies show that cost is the main driving force to fuel switching in both fuel and feedstock applications [33–35].

We also calculate the *CO_2 emission reduction* that can be achieved with bio-based products in comparison to their petrochemical counterparts (in absolute values), thereby excluding non-CO_2 greenhouse gas (GHG) emissions and emissions related to direct and indirect land use change[7] (see Appendices A–C).

As functional units, we choose one gigajoule (GJ_{th}) of steam and one tonne of bio-based material. The system boundary of the entire analysis is defined as cradle-to-factory gate and we therefore exclude the emissions from end-of-life waste treatment (e.g. release of carbon stored in waste plastic during incineration). For bio-based materials, carbon sequestered in the products is accounted for as CO_2 removal

[4] For CHP, we allocate costs to steam based on the *exergy* content of products (i.e. exergy/energy ratio of 0.2 for low and 0.4 for medium temperature steam and 1 for electricity). An alternative approach is to estimate the total costs of the CHP system and credit the revenues from electricity co-production. However, this would introduce additional uncertainties since forecasting electricity prices is complex and prices vary widely from country to country and also within countries.

[5] The BREW model allows carrying out the economic assessment for chemicals based on their *product value*. Product value is defined as the total of the production costs and profits, and it is an approximation of the market price [32] (see Appendix C). Confidential data made available for the BREW model (2003–2006) were not used. Whenever the original calculations involved the use of confidential data, extrapolation and triangulation was applied using results published in [32,52].

[6] The system boundaries of economic data available for materials are incomparable since we have a mix of production costs and sales prices at our disposal. We therefore estimate ratios for each bio-based material relative to its petrochemical counterpart. As opposed to the case of steam, it is not possible to carry out the analysis based on the differences in absolute values.

[7] Indirect land use change related GHG emissions are excluded from this analysis given the uncertainties in the modelling efforts and the current estimates [36–39].

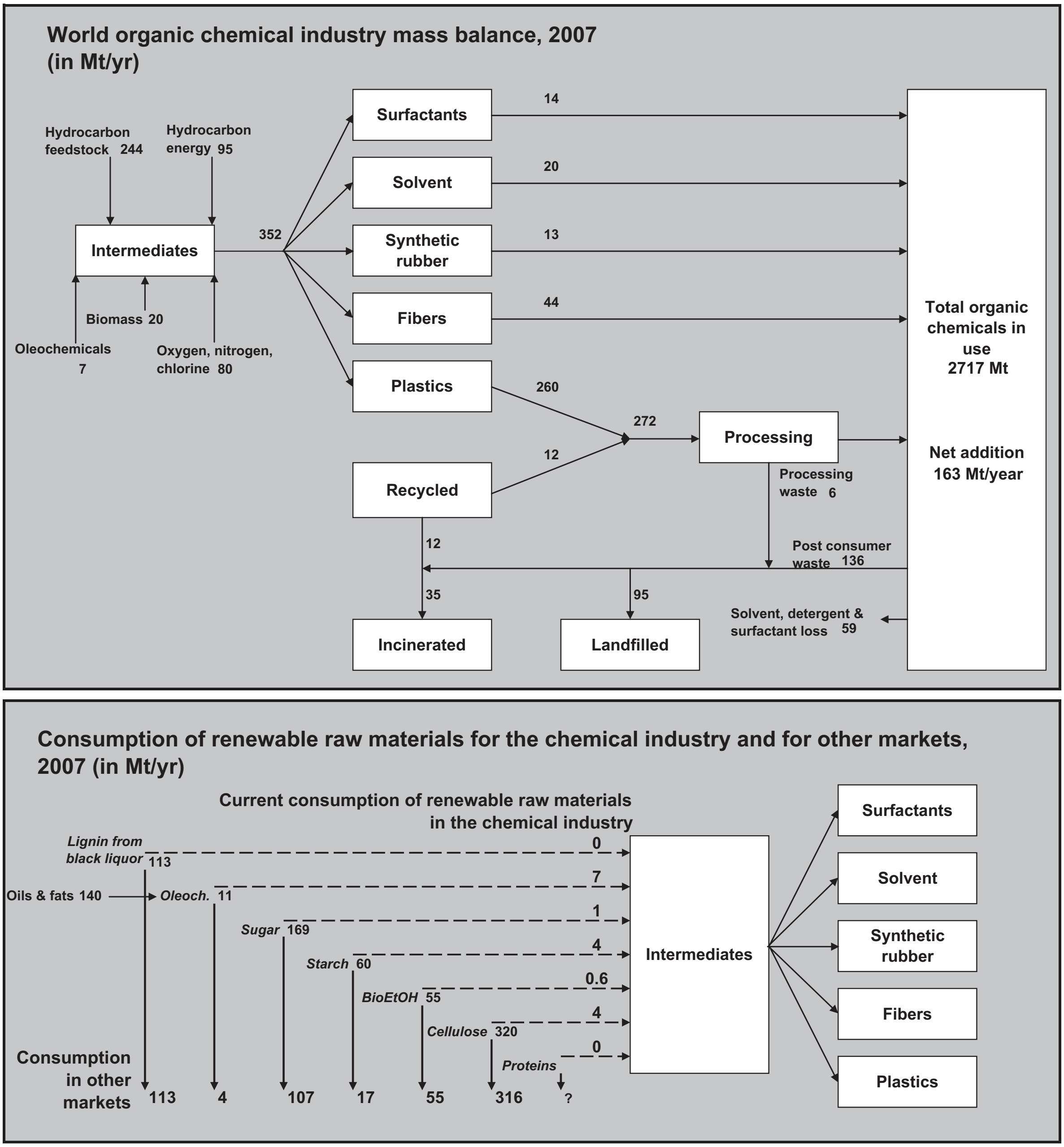

Fig. 2. World organic chemical industry mass balance and current consumption of the renewable raw materials for the chemical industry and for other markets, 2007. *Note*: Net addition is the total production of surfactants, solvents, synthetic rubber, fibres and processed plastics minus the total of post-consumer waste and materials loss. Total quantities of starch and sucrose consumed for bioethanol production are excluded.
Sources: [25,26].

from the atmosphere [40,41]. Appendices B and C provide a detailed overview of the background data and assumptions.

We compare the environmental and economic performance of bio-based steam and materials with their respective fossil fuel-based counterparts. However, the environmental performance of bio-based steam with that of bio-based material cannot be directly compared with each other. This is because of different functional units resulting in incomparable metrics, e.g. tonnes of CO_2 saved per GJ_{th} steam versus CO_2 saved per tonne of material. We therefore develop a third indicator which represents the ratio of CO_2 emissions saved per *GJ of biomass required* for a given functional unit. Unless directly reported in the sources used, we estimate the biomass required by multiplying the biomass yields in GJ biomass per hectare per year with the land use in hectares per GJ of bio-based material.[8] We limit the scope of the environmental assessment to energy and CO_2 emissions and comparison of resource use.

3.2. Scenario analysis

We now explain the methodology applied for estimating the *technical* and *economic* potentials for the years 2030 and 2050 (in EJ

[8] Annual biomass yields are between 6.5 (average of current corn and woody/herbaceous) and 17 (Brazilian sugar cane best practice) tonnes per hectare [42–44] which represent the optimistic average in temperate and tropical climate zones, respectively. We assume a LHV of 17.5 GJ per tonne for biomass. The land use efficiency of each material is provided in the Appendix [32].

Table 1
Overview of assumptions to estimate the production growth rates of the economic potentials of bio-based materials.

	Petrochemical counterpart	Development selected for *economic* potentials	Production growth rates (2009–2030)			2009 price ratio (crude oil: USD 75 per bbl)		2030 price ratio based on Updated BREW model (crude oil: USD 115 per barrel)			Reduction potentials of 2009 price ratios	
			Baseline (BaU) (% p.a.)	Optimistic technology (OT) (% p.a.)	Technical potential (% p.a.)	(A) Literature/ manufacturers (dimensionless)	(B) Updated BREW model (Sugar price: 400, current tech) (dimensionless)	(C) Sugar price: 400 (current tech) (dimensionless)	(D) Sugar price: 600 (current tech) (dimensionless)	(E) Sugar price: 600 (future tech) (dimensionless)	Energy price increase: (D) vs. (B) (%)	Techology: (E) vs. (D) (%)
Bio ethylene[a]	Ethylene	OT	7	25	32	1.2–1.7	1.4	1.0	1.3	1.2	12	4
BioPE[b]	PE	OT	11	24	30	1.2–1.3	–	–	–	–	–	–
BioPET[c]	PET	BaU	*10*	57	65	–	–	–	–	–	–	–
PHA[d]	Mix of: PE, PP, PVC, PS, PET, PUR, ABS, PMMA	BaU–OT	17	29	36	4.9–5.4	1.1	0.8	1.0	0.9	11	9
PTT[e]	Mix of: PP, PET, PA, PC, PBT, PMMA	BaU–OT	0	30	37	1.0–1.6	0.5	0.5	0.6	0.5	−9	10
PLA[e]	Mix of: PE, PP, PS, PET, PA, PMMA	OT	12	18	25	0.9–1.3	1.0	0.9	1.0	0.9	1	13
Starch Polymers[f]	Mix of: PE, PP, PS, PUR, PMMA	BaU–OT	18	18	24	1.1–3.9	–	–	–	–	–	–
Cellulosic Films[f]	Mix of: PP, PVC, PS, PET	BaU	7	33	40	3.0–4.2	–	–	–	–	–	–

Note: PE: polyethylene, PET: polyethylene terephthalate, PP: polypropylene, PVC: polyvinylchloride, PS: polystyrene, PUR: polyurethane, ABS: acrylonitrile butadiene styrene, PMMA: polymethyl methacrylate, PA: polyamide, PC: polycarbonate.

[a] Baseline production growth rate is similar to the average of all chemicals. Current price ratio is advantageous. Future energy price developments can accelerate production growth, but the future technologies will accelerate relatively lower.

[b] Assumed same as ethylene.

[c] Little information is available related to the product and therefore we assumed the production growth rates as the average of the baseline of all chemicals (presented in italics).

[d] Baseline production growth rate is highest. Current price ratio is not advantageous. Future energy price and technology developments can accelerate production growth.

[e] Baseline production growth rate of PTT is lowest among all other chemicals and of PLA is relatively high. Current price ratios are advantageous. Future technologies can accelerate production growth, but energy prices less.

[f] Baseline production growth of starch polymers is highest and of cellulosic films is similar to the average of all chemicals. Current price ratios are not advantageous. No information is available related to the contribution of energy prices and technologies.

Table 2
Levelized costs of steam production for OECD and non-OECD countries, 2009 and 2030. Costs and avoided CO_2 emissions results are expressed in USD/GJ_{th} and t CO_2/GJ_{th} respectively.

	OECD					Non-OECD					Abated CO_2 emissions[b]	
	Low biomass price		High biomass price		Average[d]	Low biomass price		High biomass price		Average[c]	OECD	Non-OECD
	2009	2030	2009	2030	2030	2009	2030	2009	2030	2030		
Biomass												
Stand-alone boiler (2 types)[a]	~8	~12	~25	~36	~32	5–8	10–13	18–27	23–36	21–29	0.069	0.065–0.089
CHP (2 types)[a]	5–8	8–11	15–18	21–24	19–22	3–8	5–11	10–20	14–26	11–21		
	OECD					Non-OECD					Abate CO_2 emissions	
	2009 average		2030 average			2009 average		2030 average				
Current fossil fuel mix[d]												
Stand-alone boilers	7–22		7–32			4–24		4–32			N/A	N/A

Note: All data refers to the crude oil price of USD 75 and 115 per barrel in 2009 and in 2030, respectively.

[a] Costs other than capital and energy are assumed to be 10% of the total steam production costs [19].

[b] Abated emissions are estimated for each region based on the fuel mix and the structure of the industry according to the international energy statistics [1]. We assume all fossil fuel use reported according to Refs. [1] is consumed for steam production. This could be abated by biomass-fired steam generation technologies (i.e., boiler, CHP). Abated emissions represent the total CO_2 emission savings from upstream activities (i.e. processing and transportation of fossil fuels (e.g. raw natural gas) to final energy carriers) and from the avoided combustion of fossil fuels. While we assume that all combustion related emissions can be abated (since new biomass sources will be planted to replace those which are combusted), we estimate that only 60% of the emissions from upstream activities can be avoided (comparison of fossil fuels with wood pellets, short rotation chips, waste wood and forest residue chips and miscanthus, switchgrass and straw bales based on [49]).

[c] Average is estimated by weighing the share of low and high biomass prices according to Taibi et al. [11].

[d] Average is estimated by weighing the projected fossil fuel mix.

of total final energy). We first estimate industrial fuel and feedstock use at sector level between 2008, in 2030 and 2050 based on the demand growth of industrial products such as steel, chemicals, paper or cement according to the projections of the International Energy Agency (IEA) [2] and autonomous energy efficiency improvements according to Saygin et al. [5].[9] The current share of industrial biomass use, which is combustible renewable and waste use mainly in the pulp and paper sector, is assumed to remain unchanged between today and 2050, i.e. approximately 10% of total global industrial fuel demand. All potentials estimated in this study are in addition to the projected biomass demand based on this share.

The geographic focus of our analysis is the total of OECD and non-OECD countries. In addition, we distinguish eight world regions for biomass used as fuel, namely OECD countries, South Africa, South America, South East Asia, China, India, Economies in Transition (EIT), and rest of the world.

We define *technical potentials* as the extent to which industrial fossil fuel use can be replaced if all technical options are exploited (in EJ of biomass and gigatonnes (Gt) CO_2 emissions abated). In the following, we explain how the *economic* potentials were determined for the year 2030:

- The approach for *bio-based steam* production is straightforward. All options which have CO_2 abatement costs below the baseline CO_2 price in 2030 in that region (USD 40 per tonne CO_2 in OECD countries and no price for CO_2 in the rest of the world) [45] are considered cost-competitive. The economic potential is defined as the extent all industrial fossil fuel that can cost-effectively be replaced by biomass based on above conditions.
- Given the lack of detailed economic data for *bio-based materials*, we follow a two-step approach.

We first estimate the annual production growth rates of bio-based materials for two scenarios (in % p.a.): (i) baseline (BaU) which represents the growth according to the bio-based capacity announcements between 2007 and 2020 [46], and (ii) optimistic technology (OT) development which refers to a scenario under favourable circumstances and an estimated 40% substitution potential for EU-25 countries by 2050 [47]. Second, we *semi-quantitatively* estimate the *economic potential* for each bio-based material based on three criteria: (i) production growth rates according to BaU, (ii) current price ratios (bio-based/petrochemical), and (iii) price ratio reductions due to the developments in energy prices and technological improvements (see Table 1). The resulting *economic potential* of bio-based materials in Mt/yr is subsequently compared to the *technical potential* to estimate the share of fossil feedstocks which can be substituted by biomass. Based on this share, the economic potential of biomass demand (in EJ) and CO_2 emissions abated (in Gt) are estimated.

We also compare the global *economic* potentials with the long-term biomass supply for 2050, the year which most studies provide estimates for (see Appendix D). For this purpose, we extrapolate the biomass use growth trends estimated for 2008–2030 to 2050.

We conduct an uncertainty analysis to account for ranges in the background data used for economic, environmental and resource assessment. We take the variations in each individual component (e.g. energy prices, capital costs, biomass yields) and apply the standard error propagation rules to quantify the total uncertainties (see ranges in the Appendix). We report these uncertainties as range (±) around the mean value. Where applicable, we also provide inner and outer ranges around the mean value which represent the minimum and maximum values of the datasets.

4. Results

We begin by presenting the cost-effectiveness of bio-based steam and materials production (Sections 4.1 and 4.2, respectively). Next, we quantify the technical and economic potentials

[9] IEA's low industrial product demand projections are 0–5% per annum (p.a.) (for various sectors and regions) and high projections are 0–8% p.a. Demand is assumed equivalent to the production without considering the trade of these products. Autonomous annual energy efficiency improvement is 1.3 ± 0.4% p.a. between 2008 and 2050.

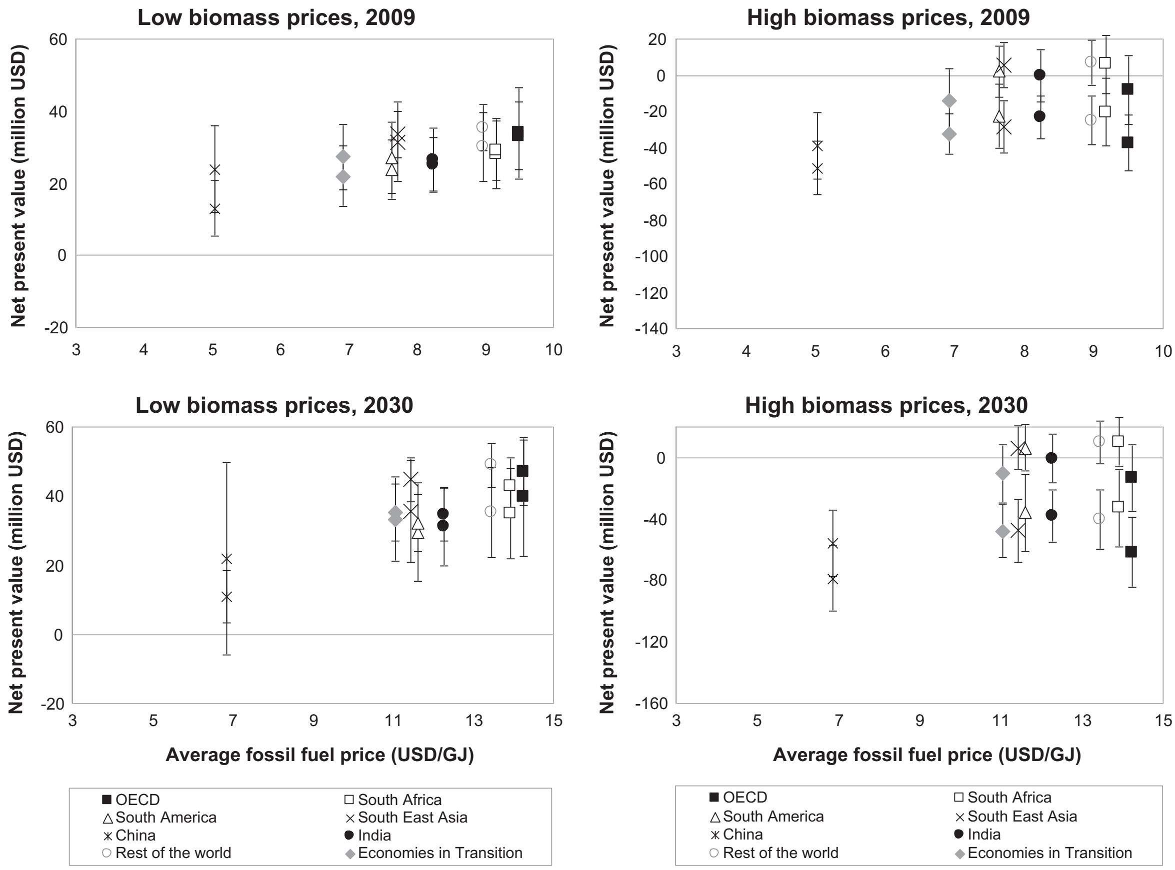

Fig. 3. NPV estimates of bio-based steam production systems relative to fossil fuel based systems; assuming 20 MW_{th} steam production capacity (typical size of the fossil fuel-based boilers), annual operation rate of 7500 h. In most countries analysed, NPVs of CHP plants are USD 5–20 million higher than those of the boilers.

of biomass in 2030 and 2050 (Section 4.3). In Section 4.4, we compare the CO_2 emission reductions by biomass use for steam and materials to their production from fossil fuels.

4.1. Biomass as fuel for steam production

Table 2 provides the production cost estimates of steam generation from biomass and fossil fuels by accounting for each region's fuel mix and energy prices. Currently, fossil fuel-based steam production costs in OECD countries (last row in the table) are estimated to range from as low as USD 7 ± 2 for coal to as high as 22 ± 3 per GJ_{th} for petroleum products (average of the fuel mix is USD 14 ± 3 per GJ_{th}).[10] In comparison, production costs from low-cost biomass sources are today estimated to range between USD 5 ± 2 from CHP plants and USD 8 ± 4 per GJ_{th} from steam boilers (the first two rows of the table). Costs from expensive sources of biomass are estimated to be three times higher, between USD 15 ± 9 and USD 25 ± 14 per GJ_{th}.

In non-OECD countries, steam production from fossil fuels is estimated to cost today between USD 4 ± 2 to USD 24 ± 4 per GJ_{th} (average of the fuel mix is USD 12 ± 4 per GJ_{th}). In regions where low-cost biomass is available (e.g., Africa, South East Asia) steam could be produced at 20–40% lower cost compared to fossil fuel based production, estimated at USD 3–8 per GJ_{th}. In regions where energy crops could play an important role, we estimate production costs at USD 10–27 per GJ_{th}. This is nearly three times higher than fossil fuel-based systems. For both OECD and non-OECD countries, the difference in steam production costs for boilers and CHP plants is largely driven by the capital and fuel costs. Compared to boilers, production costs of steam from CHP plants are similar or lower when all heat related costs of CHPs are allocated to heat production based on its exergy content.[11]

In 2030, fossil fuel based steam production costs are expected to increase by USD 5 per GJ_{th} on average due to energy price increase in all regions. For bio-based steam, we estimate a somewhat larger increase by USD 2–11 per GJ_{th} between today and 2030 which is primarily due to the larger increase in biomass prices. The effect of the increase of biomass prices is slightly tempered by the improvements in fuel utilization efficiency of boilers.

Despite a number of methodological differences between this study and the studies by IEA (Annex A of [19]) and IPCC (Annex III of [13]), our estimates for boiler systems compare well with the findings of both studies (average USD 33 per GJ_{th} for biomass pellet fired boiler systems) if similar background data are assumed. For biomass prices of USD 5–12 per GJ, IEA [48] estimates steam production costs of USD 8–19 per GJ_{th} by 2030 which confirms our findings at similar biomass prices. Our

[10] The production cost range of USD 7–22 per GJ is due to generation from different types of fossil fuels. In comparison, the ± range refers to the uncertainties around the mean value due to variation of all production cost factors except for fossil fuel prices.

[11] We also analyse the production costs by taking into account the total CHP system costs and by crediting the revenues from electricity co-production. By assuming that electricity is sold at market price, we estimate similar production costs as based on *exergy* allocation. However, in reality, CHP plant owners could sell their electricity lower than the market price. In this case, heat production costs would be on average USD 5 per GJ_{th} higher than our estimates.

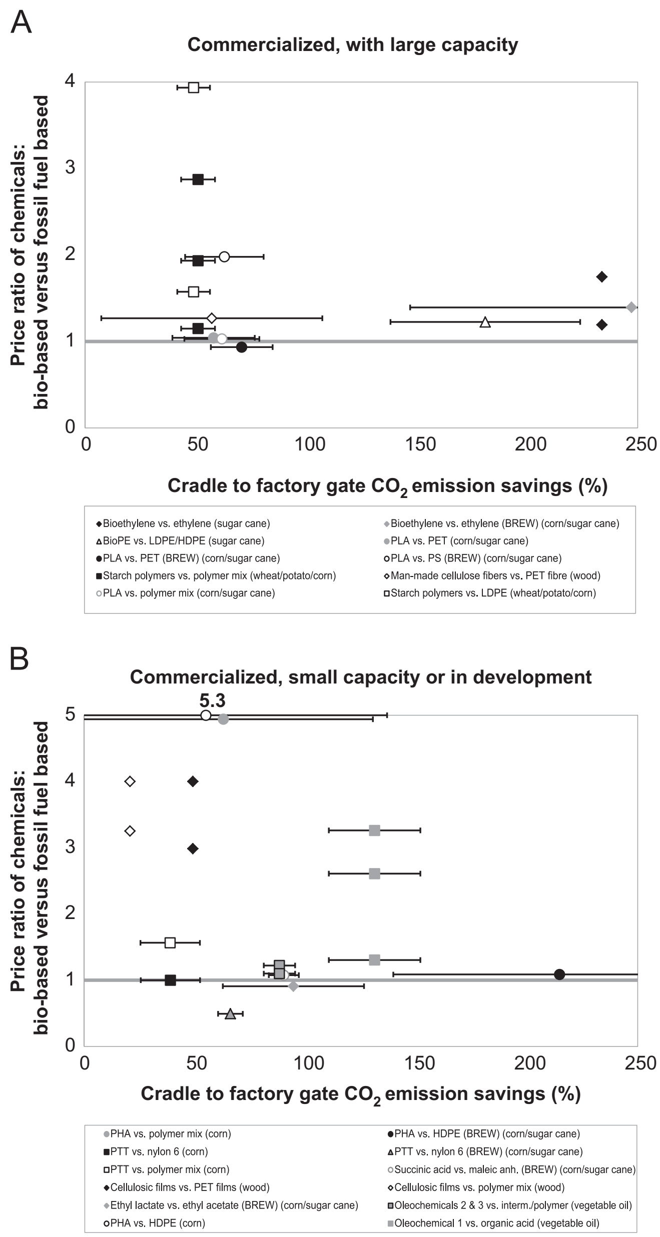

Fig. 4. Price ratios (2007–2011) and CO_2 emission savings of bio-based materials. For materials studied with the updated BREW model, state-of-the-art corn and sugar cane routes are selected for a sugar price of USD 400 per tonne; all other data points are based on price data originating from companies or literature.
Source: See Appendix.

estimates for CHP plants for low-cost sources of biomass (USD 5–11 per GJ_{th}) are similar to the findings of [23] (USD 10 per GJ_{th}) for biomass prices of USD 3–4 USD per GJ despite differences in allocation methodologies.

According to Fig. 3, steam production from biomass residues in boilers and CHP plants is currently cost-competitive (NPV > 0). In contrast, only in a few regions steam can be cost-effectively produced from biomass energy crops (NPV 0–10 million USD), namely in South East Asia, South America and Africa. In 2030, cost-competitiveness of bio-based steam production remains similar to today's low-cost and expensive biomass sources. There are opportunities in countries with biomass residues or existing waste streams in selected industries. The NPV estimates are higher in regions with high fossil fuel prices and vice versa.

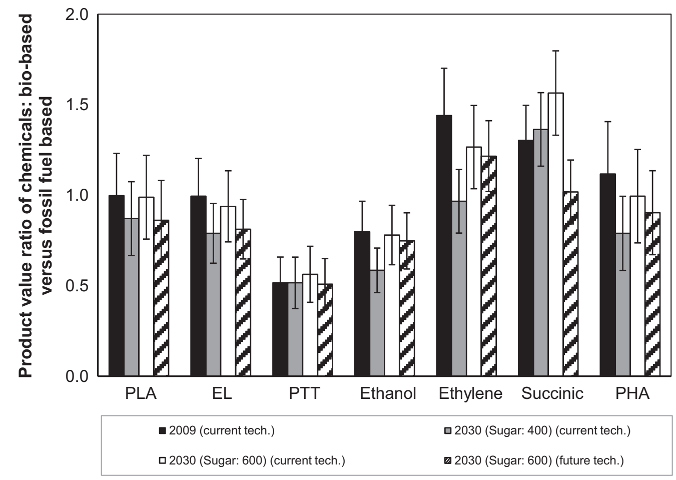

Fig. 5. Development of the product value ratios of selected products today and in 2030, assuming a crude oil price of USD 75 and 115 per barrel respectively. The assumed sugar prices (in USD/tonne) are given in brackets. PLA is compared to PET and PTT is compared to nylon 6.

4.2. Biomass as feedstock for materials production

Fig. 4 plots the current CO_2 emission savings achievable by bio-based materials versus their current sales price ratios relative to the petrochemical equivalents (price ratio < 1 is cost-competitive). While a single data point for the price ratios is shown due to limited data availability (on *y*-axis), a range for emission savings is presented since more data is available (on *x*-axis) (see Appendix C for detailed results).

For bio-based materials which are already commercialized at large scale (i.e. bio-ethylene, bio-PE, PLA, starch polymers and man-made cellulose fibres; see Fig. 4a), we estimate price ratios between 0.9 ± 0.2 and 3.9 ± 1.0 where two-thirds of the cases are between 1.0 and 1.8:

- According to IRENA estimates [50], the current worldwide production costs of bio-based ethylene are on average 50% higher compared to the production of ethylene in the steam cracking process (varying from slightly higher production costs in Brazil/India to 2–3 higher values in Europe/North America). The updated BREW model indicates a similar ratio of 40%. Furthermore, bio-PE (produced in Brazil from sugar cane) is currently sold about 25% more expensively compared to petrochemical PE [51].
- Based on data from manufacturers and the updated BREW model, PLA could have a price ratio of 0.9–1.2 compared to PET which it currently substitutes. When PLA is compared to the mix of all polymers it could theoretically replace [25], its price could be 20% higher.
- For starch polymers, our comparison yields price ratios which are 1.6–3.9 times higher compared to low-density polyethylene (LDPE) and 1.1–2.9 higher compared to the entire polymer mix which they could replace.
- We estimate that man-made cellulose fibres are only 10–30% more expensive than cotton, PET or polypropylene (PP) fibres which could be explained by the large market size already achieved.

In comparison, the economics are less favourable for materials which currently have smaller capacity or are only in development (see Fig. 4b). We estimate that in half of the cases current price ratios are between 1 and 2, and in the other half larger than 2:

- Based on data from manufacturers, the current price ratio for PTT is 1.0 ± 0.3 relative to nylon 6. Its price ratio is 60% higher

when compared to the average price of the entire polymer mix it could replace [25]. Similarly, the current price ratios for polyhdroxyalkanoate (PHA) are 3.5 ± 1.0 compared to high-density polyethylene (HDPE) and 3.1 ± 0.8 compared to the polymers mix it could replace respectively [25]. We estimate much lower price ratios of 0.5 ± 0.1 for PTT and of 1.1 ± 0.3 for PHA based on the updated BREW model (compared to nylon 6 and HDPE, respectively).

- Based on data from manufacturers, the current price ratio of oleochemicals is 1.1–3.3.
- According to the updated BREW model, both succinic acid and ethyl lactate are cost-effective and have product values which are similar to the petrochemical equivalents (1.1 ± 0.2 and 0.9 ± 0.2, respectively). In comparison, cellulosic films have much higher price ratios estimated at 3–5 when compared to PET films.

Our analysis shows that bio-based materials are currently clearly more expensive than their petrochemical equivalents. Bio-based materials are usually cost-competitive when replacing high-value petrochemicals which typically represent the current situation. The updated BREW model, which takes a generic and harmonized approach to estimate the product values, yields lower price ratios for some materials (e.g. bio-ethylene, PTT, PLA) compared to the sales price ratios (see Fig. 4). This is also confirmed by the study of Hermann et al. [52] which estimates product value ratios less than 1 for most BREW products for a crude oil price of USD 70 per barrel and a sugar price of USD 400 per tonne. Today's higher sales prices are explained by the fact that most bio-based polymers are at their early phase of production and commercialization. However, in the short to medium term there could be opportunities to sell bio-based materials at lower prices than today as they reach a higher market share.

We now discuss the potential developments in the economics of bio-based materials until 2030 according to the updated BREW model (see Fig. 5). If sugar prices remain at the 2009 level (USD 400 per tonne), but if the crude oil price increases from USD 75 to 115 per barrel in 2030 [45], the product value ratios would either remain same or decrease by about 0.1–0.5 compared to the current product value ratios (0.5–1.4)[12] (second bars from left). Making the more realistic assumption that future fossil fuel and biomass prices are coupled, sugar prices may increase from today's level of USD 400–600 per tonne by 2030 [53]. In this case, the ratios by 2030 would be either equal to or only slightly lower than today (0.1–0.2) (third bars from left). Depending on the product, the effect of increasing sugar prices is partly compensated by innovations in production technology, reducing the product value ratios by 0.1–0.5 compared to the level with high energy prices and current technology (fourth bar as compared to third bar). In 2030, some products (i.e. ethanol for chemical purposes, PTT and ethyl lactate) are more attractive compared to their petrochemical equivalents (<0.8), while others are expected to be less competitive.

4.3. Technical and economic potentials of biomass use in industry: 2030 and 2050

We estimate total global fossil fuel demand for low and medium temperature steam production to reach approximately 51 EJ/yr by 2030 (excluding pulp and paper sector biomass demand of ~11 EJ) (see Table 5). Total required biomass volume is 5–10% higher in order to meet this demand (*technical* potential) given the only limited differences assumed in fuel conversion

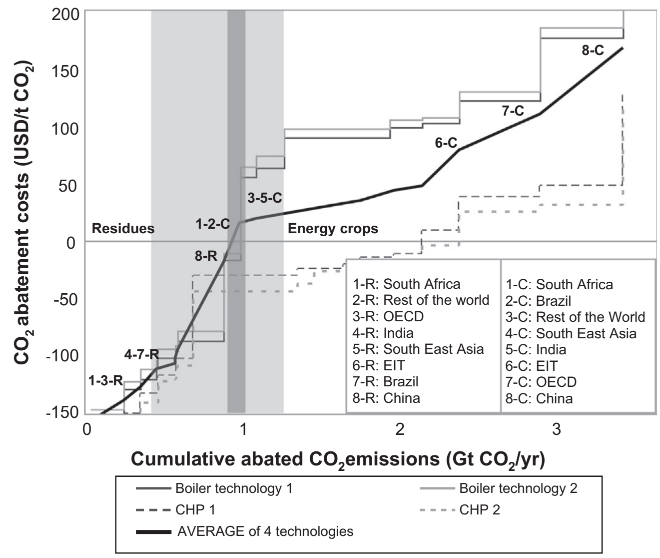

Fig. 6. Estimated CO_2 abatement cost curve for bio-based steam production, 2030 (for low production growth scenario of IEA [2]).

efficiencies of biomass and fossil fuel-based combustion technologies. Achieving the technical potentials would abate 3.2–3.7 Gt CO_2 emissions in 2030 (Table 5).

The economics of CO_2 abatement by bio-based steam production are represented by Fig. 6. Due to lack of insight into the shares of the various technologies the arithmetic mean of all technologies was determined, albeit with a differentiation by world regions. About 25% of the total CO_2 emissions (indicated by dark grey shaded bar) can be abated at costs below the CO_2 price of USD 40 per tonne CO_2 in OECD countries. Another 0–15% of the total CO_2 emissions could be saved below USD 50 per tonne CO_2 by expensive biomass sources. The remainder of the emissions (60–75%) could be avoided at a cost between USD 50 and 200 per tonne CO_2. Based on the difference in steam production costs of fossil fuels and biomass and accounting CO_2 prices, we estimate an economic potential of 13 EJ biomass (Table 5). This translates to 0.9 Gt CO_2 emissions which could be cost-effectively abated by 2030.

These results are based on our estimates that steam production from biomass residues is cost-competitive compared to fossil fuels and all biomass residues are used which represent about 20–25% of the total biomass supply potential according to Taibi et al. [11]. Based on other literature, we identify a wide range for biomass residue supply (see Appendix D) and *economic* potentials of biomass which could result in 0.4 (minimum) to 1.3 (maximum) Gt CO_2 emission reductions. This requires 5–22 EJ biomass (indicated by light grey shaded bars in Fig. 6). All steam demand of the food, textile, transport equipment, machinery, mining and quarrying and up to 85% of the demand in the pulp and paper and *non-specified* sectors can be provided by biomass. In comparison, biomass can provide only half of the total the chemical industry's total demand, and a much lower share ($<10\%$) in the basic metal and non-metallic minerals sectors. These sectors require other forms of biomass (e.g. charcoal) and renewable energy sources (e.g. hydrogen) to increase their renewables share [54].

Global synthetic organic materials production is expected to grow from 350 Mt/yr today to between 500 and 570 Mt/yr by 2030 [2]. A total of 32–36 EJ of primary biomass will be required by 2030 to reach the *technical* potential for bio-based materials production (Table 5).

Based on the 12 materials presented in Fig. 4, between 40% and 140% of the CO_2 emissions associated with the petrochemical equivalents can be saved (crediting the sequestered bio-based

[12] Succinic acid is an exception since its product value ratio increases by 5% as compared to all other chemicals where the ratios decrease. This is explained by the decreasing product value of maleic anhydride (petrochemical substituted) in response to increasing crude oil prices as its production process is a large steam exporter.

Table 3
CO_2 abatement cost estimates for bio-based materials, 2009. All values are expressed in USD per tonne of CO_2 abated.

	Petrochemical counterpart	Literature/manufacturers		Updated BREW model (current/future technology and sugar price USD 400 per tonne)	
		Low	High	Low	High
Bio ethylene	Ethylene	65	140	125–175	250–400
BioPE	LDPE & HDPE	95	150	–	–
PHA	HDPE	> 1000	> 1000	30–60	120–160
	Polymer mix	> 1000	–	–	–
PTT	Nylon 6	0	–	~ –550	~ –480
	Polymer mix	> 980	> 2000	–	–
PLA	PET	–295–480	–160–290	–110 to –80	~0
	Polymer mix	–265–360	–155–245	–	–
Starch polymers	LDPE	380	> 1000	–	–
	Polymer mix	650		–	–
Cellulosic films	PET films	> 1000	> 1000	–	–
	Polymer mix	> 1000	> 1000	–	–

carbon). These savings translate to an average of 2.5 ± 1.6 t CO_2/t bio-based material which confirms the findings of Weiss et al. [55] who determine a saving potential of 3 ± 1 t CO_2 eq. relative to conventional materials. For example, bio-based ethylene offers CO_2 savings from 1.9 to 5.3 t depending on feedstock type (e.g. sugar cane, corn) with a 3.7 ± 1.4 t CO_2/t average. Similarly, various bio-based polymers offer savings between 0.2 and 4.5 t CO_2/t with a 2.3 ± 1.5 t CO_2/t average. For further analysis, we select the 7 most important bio-based polymers according to Shen et al. [25] which could technically replace half of the total petrochemical polymers and fibre consumption worldwide today. Based on these polymers, we estimate a *technical* CO_2 emission reduction potential of 0.3–0.7 Gt CO_2 in 2030 (Table 4). Assuming the same potential for the remainder of the organic materials production, a *technical* reduction potential of up to 1.4 Gt CO_2/yr is estimated.

We estimate the total *economic* potential of bio-based materials production at 120 ± 30 Mt/yr by 2030. The full range from BaU to OT scenarios covers bio-based production volumes of 40 Mt (minimum) to 225 Mt (maximum) per year. Bio-PE, PLA and PHA production are expected to have the largest potentials based on their current sales price ratios and their high BaU production growth (see Table 1). In comparison, cellulosic films and PTT production may hardly go beyond the BaU scenario due to their high price ratios. Based on these production volumes and a weighted average CO_2 saving potential of 2.8 ± 0.9 t CO_2/t (Table 5), we estimate a total *economic* CO_2 emission saving potential of ~0.4 Gt CO_2/yr worldwide.[13] This is approximately a quarter of the technical potential and would require ~8 EJ biomass in 2030 (Table 5). The full range of emission reductions according to the BaU and OT scenario developments are 7% and 37% of the technical potential, thereby requiring in total 2 and 12 EJ additional biomass, respectively.

Estimating CO_2 abatement costs for bio-based materials is rather difficult. The value chain of the end products is longer and the structure of the economic data available is complex since it is not limited to the production costs only, but includes other parameters such as price premiums. We nevertheless provide indicative estimates in Table 3 showing that profitable areas for bio-based materials are limited and it would be more expensive to abate CO_2 emissions with bio-based materials compared to steam. This comparison refers to polymers in primary forms, while the end application and waste management also contribute to the life cycle costs. Since other forces beyond simple economic indicators drive the deployment of materials production from biomass (especially strategic considerations), future policy discussions should consider aspects apart from abatement costs.

For industry, we estimate an *economic* potential of approximately 22 EJ biomass use as fuel and as feedstock in 2030 (with a range of 9–43 EJ covering the BaU and OT scenario developments) (Table 5). The economic potential is equivalent to an abatement of 1.3 Gt CO_2 emissions.

For 2050, we estimate an economic potential of 38–43 EJ biomass use by extrapolating the estimated developments between today and 2030 (with a range of 21–57 EJ). Reaching these potentials would save 1.9–2.2 Gt CO_2/yr in 2050 which is equivalent to a 37% reduction compared to no use of biomass. Earlier studies estimated total economic potential for industrial biomass use up to 40 EJ by 2050 mostly as fuel including the demand in high temperature applications [2,11,33]. Our findings of 51–56 EJ (which includes the pulp and paper sector demand of approximately 13 EJ) are higher than these findings mainly due to the high potentials estimated for feedstock use (16 EJ). Biomass use as feedstock is nearly high as fuel for steam showing the importance of substituting fossil fuel-based feedstocks. About 85% of the total global biomass demand is estimated in non-OECD countries (~21 and ~36 EJ in 2030 and 2050, respectively) with OECD countries accounting for the remainder 15% (~3 and ~5 EJ in 2030 and 2050, respectively) (Fig. 7). Demand from Asia, followed by the African and South American countries will account for most global demand.

4.4. Comparison of the CO_2 emission savings performance of biomass use as fuel and feedstock

1 GJ biomass abates on average 0.070 ± 0.005 t CO_2 when used for steam generation in boilers or CHP plants which reach efficiencies close to fossil fuel equivalents (full range indicated by the bandwidth from 0.066 to 0.079 depending on the regional fuel mix and the industry structure) (Table 5). 30–45% lower CO_2 emission savings per GJ of biomass is estimated for the weighted average of bio-based materials which replace the current mix of *all* petrochemical plastics (0.044 ± 0.022 t CO_2/GJ). For current technology, the savings are as low as 0.020 ± 0.022 t CO_2/GJ for cellulosic films and as high as 0.132 ± 0.063 t CO_2/GJ for starch polymers. Saving potential of each material is determined by: (i) its land use efficiency (i.e., GJ biomass required per tonne of material as a function of crop type, biomass yield and the chemical structure of the polymer), (ii) its CO_2 emissions savings compared to the reference product chosen (t CO_2 saved per tonne of bio-based material), and (iii) mix of reference products and their production volumes which can be technically substituted. The comparison shows that there are many bio-based polymers which can compete with biomass as fuel. However, for

[13] The saving potential may change depending on which materials are deployed in the estimated economic potentials, what their production volumes are and their CO_2 saving potential.

Table 4
Economic potentials of bio-based materials production and the total CO_2 emission savings in 2007 and by 2030 worldwide and in OECD and non-OECD countries.

	Current sales price ratio (compared to polymer mix) (dimensionless)	CO_2 emission savings (t CO_2/t)	Bio-based production (2007)	Petrochemical based production (2007)	Petrochemical based production (2030)		Total CO_2 emission saving potential (2030)		*Economic* bio-based production (2030)[a]	Total *economic* CO_2 emission saving potential (2030) (Mt CO_2/yr)
			Global (kt/yr)	Global (Mt/yr)	OECD (Mt/yr)	Non-OECD (Mt/yr)	OECD (Mt CO_2/yr)	Non-OECD (Mt CO_2/yr)	Global (Mt/yr)	
Bio ethylene	1.2–1.7	1.9–5.3	375	115	56–58	100–225	106–308	237–787	90 (2–90)	109–345
End-products[b]										
BioPE	1.3	2.4–4.2	200	46	22	49–59	52–96	116–244	25 (2–25)	54–107
BioPET	–	1.9–2.5	0	5	3	6–7	5–7	11–17	0.01 (0–3)	0.002
PHA	1.1–3.1	1.4–4.0	80	27	13	29–35	17–53	39–134	6 (3–26)	7–23
PTT	0.5–1.5	1.1–1.9	10	7	3–4	8–9	2–6	4–16	0.01 (0–4)	0.001
PLA	0.9–2.0	1.2–2.1	229	12	6	13–15	6–11	13–29	7 (3–10)	7–14
Starch polymers	1.5–3.9	1.7–3.6	153	11	5	11–15	9–19	20–49	7 (6–7)	12–24
Cellulosic films	2.0–3.9	0–1.9	10	11	5–6	12–24	0–10	0–25	0.1 (0.1–7)	0–0.1
Total of selected polymers				118	57–59	130–150	90–210	202–514	43 (15–82)	79–169
Total of polymers				240	115–120	260–310	184–409	410–1044	88 (31–168)	161–342
Total of synthetic organic materials				320	155–160	345–410	245–545	547–1392	120 (40–225)	215–457

Note: Total of seven polymers could technically replace half of the total polymers production in 2007 [25,56].
[a] In brackets we provide the full range of bio-based materials production.
[b] All polymers are 100% bio-based with the exception of PTT and starch polymers; PTT is partly produced from petrochemical terephthalic acid and starch polymers typically contain petrochemical polyvinyl alcohol, polycaprolacton or another petrochemical compound.

some polymers biomass use as feedstock could be less attractive from a land use point of view.

There are substantial differences across the various types of bio-based materials, with starch polymers offering clearly larger savings than all others (Fig. 8). The solid line (horizontal) represents the savings compared to the entire substituted polymer mix [25], with solid error bars (vertical) representing different grades of a given type of bio-based polymer and/or different production processes. More importantly, the dashed error bars (vertical) represent the saving potentials when comparing bio-based materials to individual petrochemical equivalents. Substituting fossil fuel based polyamide (PA), polymethyl methacrylate (PMMA) and polycarbonate (PC) by PLA, BioPTT, starch polymers or PHA offers CO_2 emission reductions above 0.1 t CO_2/GJ biomass, which is the upper level of savings by bio-based steam (represented by the upper dashed horizontal line). This shows that very attractive options do exist which, however, require dedicated research and development (R&D). Furthermore, instead of using bio-PE and bio-PET to replace petrochemical PE and PET, respectively, there may be other polymers fulfilling the same functions may offer larger CO_2 savings (not shown in Fig. 8). This is in line with the findings of Bos et al. [57] who conclude that PLA should be preferred over bio-PE on the basis of land use efficiency. This is a critical finding given the increasing pressure on land resources.

5. Discussion

We first discuss the estimated economic potential of industrial biomass use in 2050 and identify the main barriers to its deployment. Next, we discuss the technology and policy needs to accelerate industrial biomass use and how these barriers could be eliminated based on the results of a sensitivity analysis. Finally, we discuss the main uncertainties of our data and methodology and we identify future research needs.

5.1. Main barriers

Industrial demand for biomass could be supplied in three forms: dedicated energy crops, agricultural and forestry residues and waste (incl. animal manure, municipal waste). Energy crops are expected to supply a larger share of the total demand (see Section 4). Demand will be mainly covered local biomass production. Besides the industry sector, transport, power and construction sectors also aim to increase renewable energy use. As a result, competition and demand for biomass will increase. As local production may not meet all demand some regions will rely on imports (e.g. some OECD countries). Based on 17 studies, biomass supply potentials are found to range from 75 to as high as 1500 EJ/yr in 2050 (see Fig. 9). More recent supply estimates tend to narrow the bandwidth down to between 75 and 215 EJ/yr biomass by 2050 (see white filled squares in Fig. 9) due to constraints on resource availability and other uncertainties in the development of food, feed and water demand (see also Ref. [58]). We regard this range as the sustainable biomass supply potentials for this study.

Economic potential of biomass use in industry (51–56 EJ), would require 25–65% of the global supply potential in 2050. Meeting these potentials would substitute a quarter of industrial total fossil fuel demand (140–160 EJ). The remainder demand and the related industrial CO_2 emissions needs to be reduced by other measures. Our assessment shows that biomass can play a crucial role for industry next to other measures. However, the location of the plants (i.e. distance to resource) and their access to biomass supply will be crucial to realize these potentials. Biomass supply in some regions is limited especially when considering the competition for the same resources from other sectors. Continuous supply of energy is a major concern for the industry and it will be of particular challenge to

Table 5
Technical and economic potentials of global industrial biomass use and CO_2 emission reductions in 2030 and 2050.

	Technical potential (with autonomous improvements)		Economic potential (with energy efficiency)	
	2030	2050	2030	2050
Biomass use (EJ/yr)				
Feedstock	32–36	42–48	8–9	15–17
Fuel	51–55	58–66	13–14	23–26
Total	83–91	101–114	21–23	38–43
CO_2 emission reductions (Gt CO_2/yr)				
Feedstock	1.3–1.4	1.7–1.9	0.3–0.4	0.6–0.7
Fuel	3.2–3.7	3.4–4.1	0.8–1	1.3–1.6
Total	4.5–5.1	5.1–6	1.2–1.3	1.9–2.2

Note: Potentials exclude biomass use in pulp and paper sector (11 EJ and 13 EJ by 2030 and 2050, respectively).

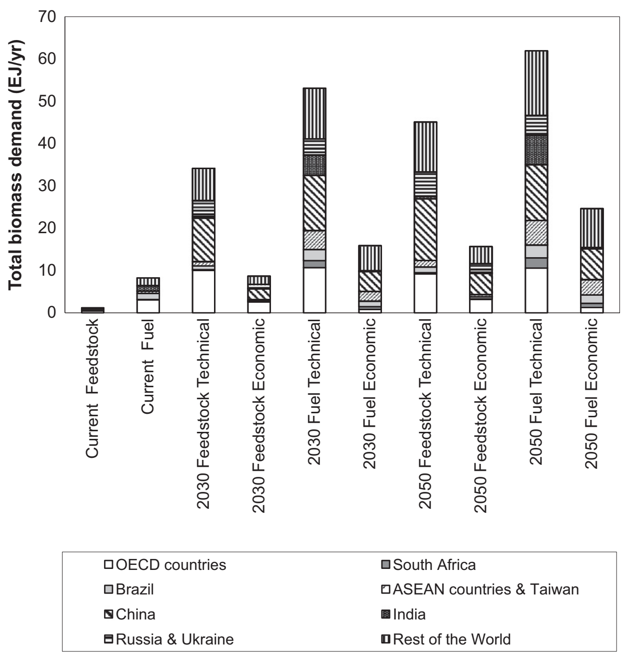

Fig. 7. Total biomass demand for feedstock and fuel purposes by regions/selected countries, 2030 and 2050. Bars represent the average of the low and high production growth scenarios. *Note*: Potentials exclude the use of combustible renewables and waste.

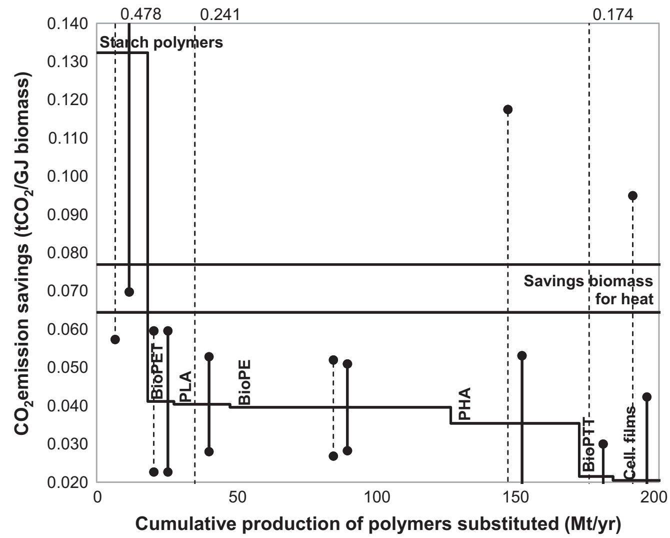

Fig. 8. CO_2 emission savings of seven polymers as a function of the cumulative production of polymers they can substitute. *Note*: Black and grey error bars show the highest and lowest savings achievable by different grades of a given type of bio-based polymer and/or different production processes and feedstock types compared to the polymer mix and individual petrochemical polymers respectively; the chosen polymer mix differs by type of bio-based polymer (e.g. PET, PE, PP, PS). Dashed horizontal lines indicate the low and high end of the savings that can be achieved by producing bio-based steam.

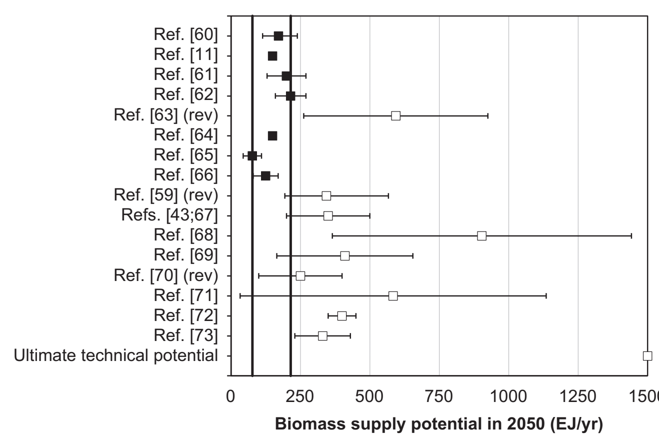

Fig. 9. Literature review of biomass supply potentials, 2050. (rev) refers to the range taken from review studies [11,43, 59–73].

substitute fossil fuels use in large plants because of storage requirements and seasonal factors affecting biomass availability [74]. The comparatively high cost of biomass use in many applications is another barrier. With increasing demand to supply ratios, prices of biomass would increase reducing its cost-competitiveness. Other technical barriers are to integrate biomass conversion in existing chemical or food plants which are integrated in terms of energy and material flows.

5.2. Further outlook to technology development and policy needs

For the case of steam boilers, we quantify the sensitivities of the NPV to the changes in selected production cost factors for low and high biomass prices (see Fig. 10). The results highlight that low biomass and high fossil fuel prices are pre-requisites for cost-competitive bio-based steam production (see also Section 4.1). However, high fossil fuel prices are not sufficient to ensure the cost-competitiveness of expensive biomass. Furthermore, compared to cheap fossil fuels it becomes difficult for biomass to compete (NPV < 10 million USD). Recent developments in the US chemical industry show that investments in the chemical industry have increased with the supply of low cost shale gas [75]. In view of the uncertainties in the development of future energy prices as well as the lower maturity of renewable energy technologies relative to fossil fuel alternatives, investors may consider higher discount rates than used in this analysis to minimize the associated risks. If we increase the discount rates from the default values of 10–15% for various regions to 20% worldwide, we see a decrease in the NPV of bio-based steam by 12 million USD (from 33 to 21 million USD), but steam production from cheap biomass sources still remains an attractive option. Technological learning resulting in reductions in capital costs of boilers (applies particularly to medium temperature steam applications which require relatively expensive equipment [21]) as well lower operation and maintenance costs (expressed as share of other production costs in Fig. 10) and improvements in boiler efficiencies could contribute to increased cost-effectiveness of bio-based steam production. Lack of detailed data limits the possibilities of sensitivity

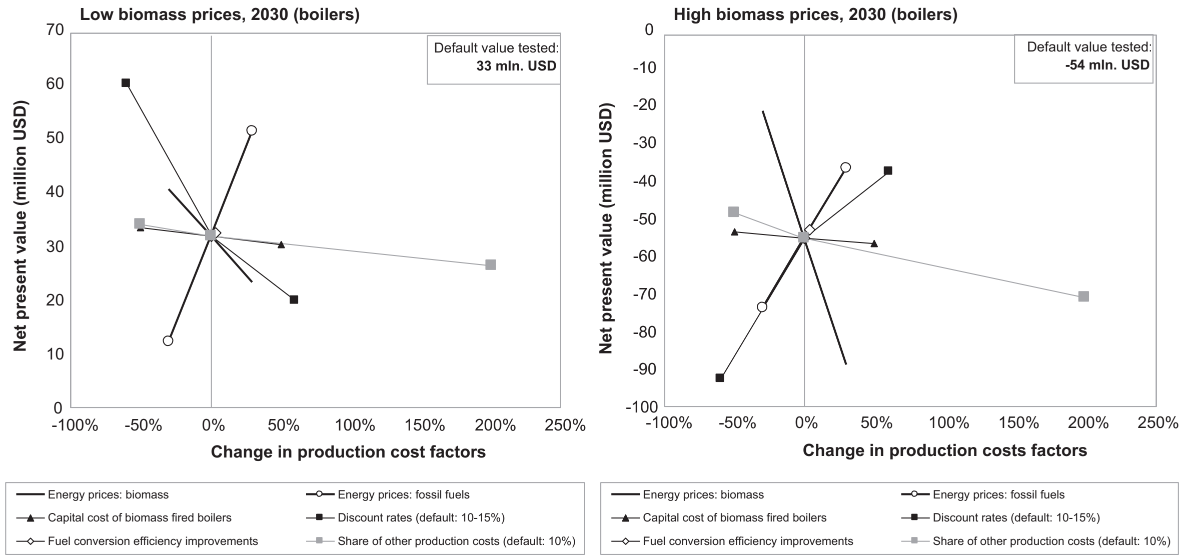

Fig. 10. Sensitivities of the NPVs of biomass-fired steam boilers to the changes in selected steam production cost factors (in %) expressed in million USD for low and high biomass prices, 2030; assuming 20 MW_{th} steam production capacity and an annual operation rate of 7500 h. Note: In both figures, the directions of the changes in NPV values are identical for all the factors tested with the exception of discount rates. In the right figure, NPV improves when discount rates are increased which is explained by the fact that steam production from biomass energy crops is anyway not economically viable and higher discount rates reduce the losses.

analyses for bio-based materials; however, our earlier findings in Fig. 5 show that feedstock costs (i.e. sugar prices) as well as the technology employed (i.e. current state-of-the-art technologies or future technologies) play a major role for the cost-effectiveness of bio-based materials.

Given the uncertain energy and feedstock prices, carefully crafted policies will be required to ensure a level playing field among the various uses of biomass (e.g. [76,77]). For example, pricing of CO_2 emissions up to USD 100 per tonne by 2030 [45] would already double the economic potentials of steam production (based on CO_2 abatement costs) and would reduce the price ratios of bio-based materials by 5–15%. Other financial instruments (e.g. price premiums in the short-term, subsidies; [78,79]) can help bio-based materials to secure increased market share. Biomass needs to be used in applications which are cost-effective and where emission reductions can be maximized with resource effective applications to ensure supply security (e.g. [57]). In the case of steam production, available biomass should be allocated primarily to medium temperature applications and less to provide low temperature steam production for which other renewable alternatives exist (e.g., heat pumps, solar thermal, geothermal [11]). Since a carbon source will always be required for materials production, a higher share of biomass can be allocated for feedstock use. Our analysis showed that the related potentials are as high as the potentials for steam production and that switching to biomass feedstocks is therefore equally important. Given poor land use efficiency in some applications, policies need to steer the industry to develop more resource efficient and environmentally friendly materials for bulk applications. In certain markets, bio-based materials outpace their conventional counterparts already today (see Fig. 8). Since the development and commercialization of more resource-efficient materials may require a relatively long period of time, other materials such as bio-based ethylene and polyolefins (e.g. bio-PE based on bio-ethanol) may gain large market shares, in particular since they can be implemented as drop-in solutions in the existing infrastructure. Policies therefore need to define sustainability criteria and provide clear guidance to the business and consumers. Policies will also need to minimize the environmental effects over the entire life cycle of products by accounting for the use phase and end-of-life stage of the bio-based materials (e.g. [79]). n view of the longer value chain of bio-based materials, there are larger innovation potentials for cost reductions and technological improvements. In comparison, bio-based steam will largely depend on the development of the differences in energy prices given the already mature steam production technologies.

5.3. *Further discussion on data and methodology and recommendations for future research*

Our findings are plausible in view of the findings of other studies, but they are still subject to uncertainties and our methodology could be improved. Further analysis would be required on the following topics:

- Future opportunities of biomass use will be determined by energy prices. A bottom-up analysis of biomass prices is essential, in particular to underpin our assumption of estimating the delivered cost of biomass based on the biomass production costs and to account for the relationship between biomass prices, its supply and distance of industry plants to resources. Cost-effectiveness of industrial biomass use would substantially change if pricing is applied.
  Potential developments in energy prices such as reduction in fossil fuel prices due to decreasing demand or large scale use of shale gas, and their implications over our findings should be further assessed which would also impact the regional potential estimates.
- Given the limited potentials of biomass supply, a bottom-up analysis of biomass supply and allocation of its use is required by accounting for the competition of biomass with other sectors, potentials of international biomass trade and accessibility to biomass for large industrial plants.
- We only analysed the potentials of two steam production technologies. Extending the analysis to cover other systems such as co-firing and multi-output systems (e.g. materials, energy production) such as bio-refineries and (polygeneration) gasification facilities would provide better insight into the potentials by also covering high temperature process heat generation.
- The system boundary of our analysis is defined as cradle-to-factory gate and it focuses on the CO_2 emissions only. Our

methodology should be extended to cover other key impact categories for biomass [48]: (i) non-CO_2 GHGs (e.g. N_2O emissions from biomass cultivation), (ii) emissions related to indirect land use change (iLUC) by reflecting all changes in the carbon stored in ecosystems, and (iii) end-of-life waste treatment of materials. These aspects have potential implications for this study's findings and they could be taken into account, e.g. via a multi-criteria analysis.
- Economic potentials of 2050 include uncertainties since they are based on extrapolation. With improved data (e.g. energy prices) and more analysis (e.g. bottom-up production cost analysis of bio-based materials and integrated modelling) these findings can be improved.

6. Conclusions

In this paper, we presented the cost-effectiveness of biomass use for the industry sector and quantified its long-term potentials. Our analysis shows that by 2030, cost-effective opportunities for biomass use amount to ~23 EJ of biomass. Economic potentials can increase to 38–45 EJ by 2050 and this can supply 25% of the total final industrial energy use. Realizing the long term opportunities will depend on the development of the biomass and fossil fuel prices. Given the sustainability concerns and the constraints on resource use, the availability of sustainable biomass is too limited to meet the potential demand from all sectors of the global economy. In terms of resource efficiency (tested for CO_2 emission savings by GJ of biomass), some bio-based materials score worse than bio-based steam while others score clearly better. During the development and commercialization of bio-based heat and materials, policies need to provide guidance to business and consumers to make effective use of the limited biomass availability.

The findings of this study along with other studies could serve as a starting point to set targets for biomass use by application area. Realizing these targets will require integrated policies on energy, material, agriculture (food, feed) and resource use and international collaboration across the industry, energy and transportation sectors. For the industry sector, these policies need to trigger continuous innovation to develop improved bio-based alternatives, to ensure their cost-competitiveness and to develop and implement new technologies beyond biomass use in order to achieve ambitious CO_2 emission reductions. Regional roadmaps can provide guidance for a transition to a bio-based industry by outlining the deployment and emission reduction targets over time, required technologies, supply potentials as well as the finance and specific policy needs. This paper makes an important step forward to contribute to the development of such a roadmap.

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Appendix A. Supplementary material

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